Overview of ep/eA physics program at a future Electron-Ion Collider (EIC) facility

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The Electron-Ion Collider

Unanimous recommendation of the
QCD Town Meeting,
Rutgers University, NJ,
January 13, 2007

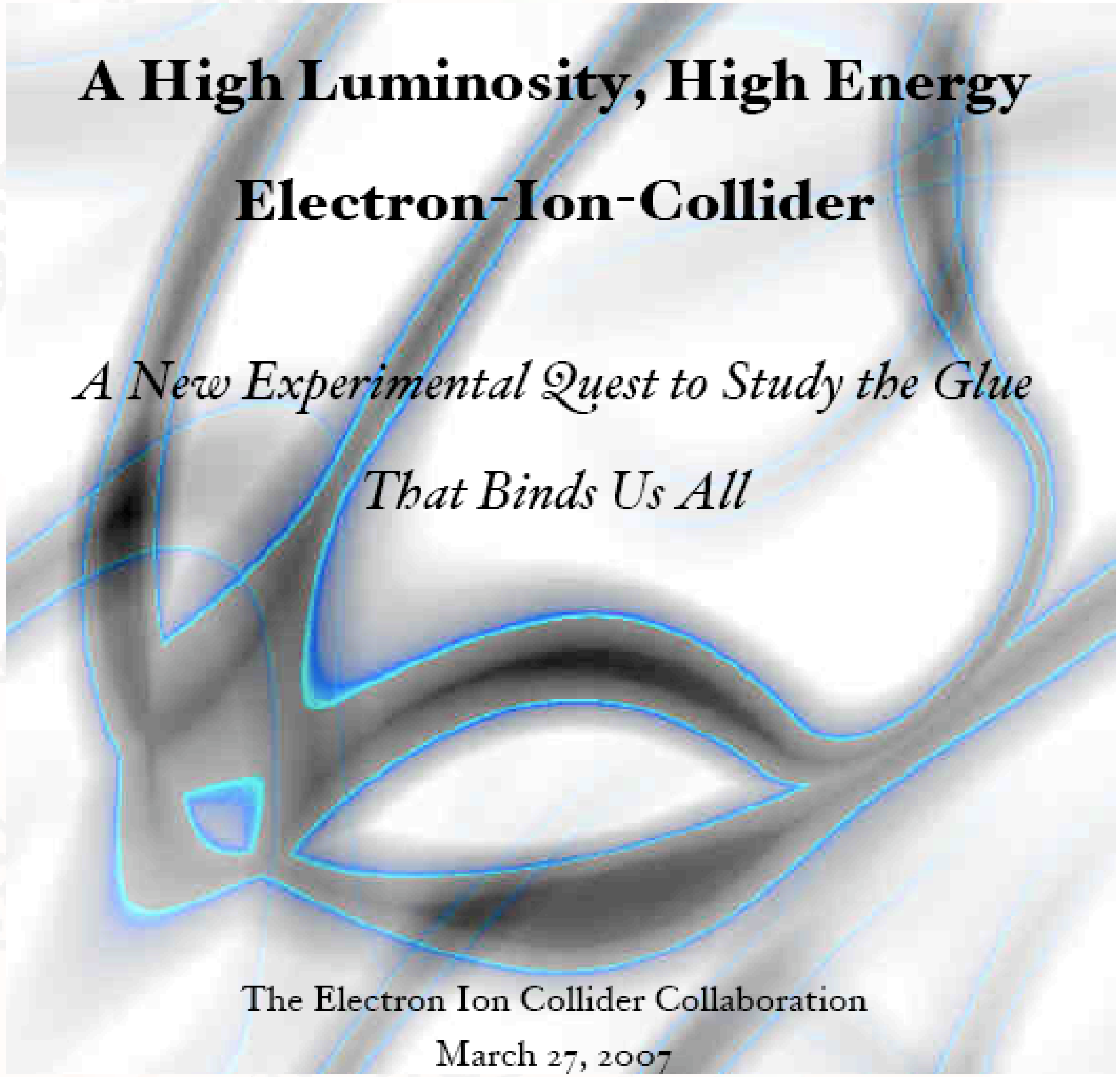
A high luminosity Electron-Ion Collider (EIC) is the highest priority of the QCD community for new construction after the JLab 12GeV and RHICII upgrades. EIC will address compelling physics questions essential for understanding the fundamental structure of matter:

- Precision imaging of the sea-quarks and gluons to determine the spin, flavor and spatial structure of the nucleon.
- Definitive study of the universal nature of strong gluons fields in nuclei.

This goal requires that R&D resources be allocated for expeditious development of collider and detector design

The Electron-Ion Collider

- EIC Whitepaper
  - Input for the NSAC LRP 2007 process

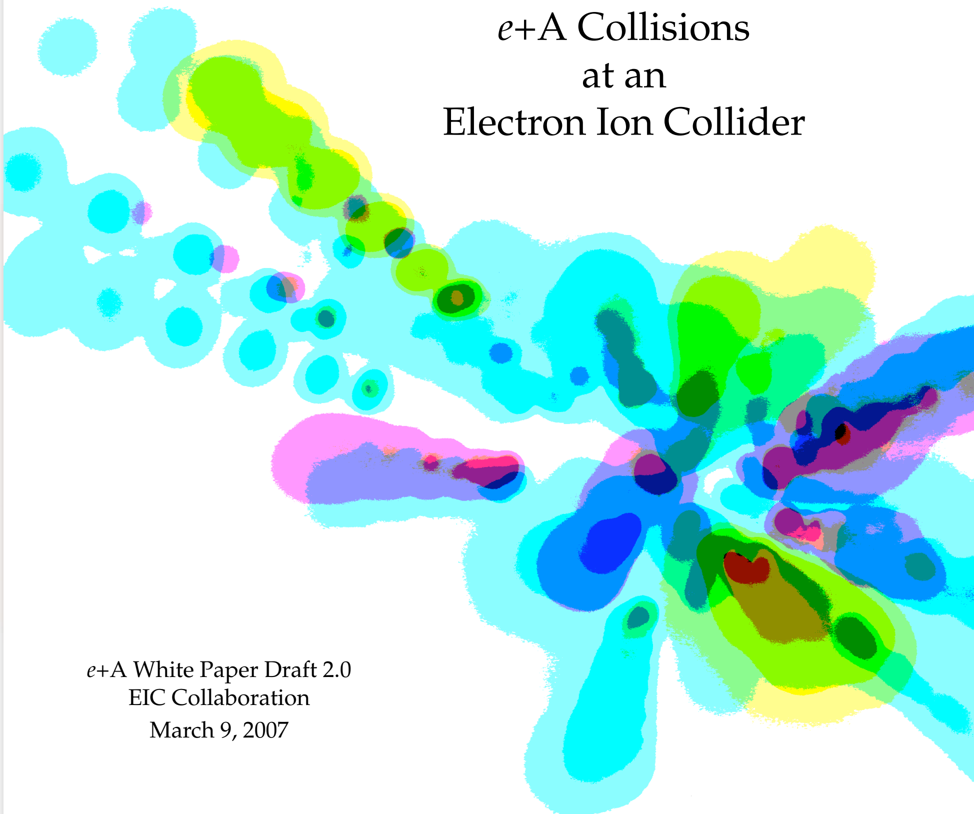


NSAC: Nuclear Science Advisory Committee

LRP: Long-Range Planning

The Electron-Ion Collider

Physics Opportunities
with
e+A Collisions
at an
Electron Ion Collider



e+A White Paper Draft 2.0
EIC Collaboration
March 9, 2007

The EIC Collaboration*

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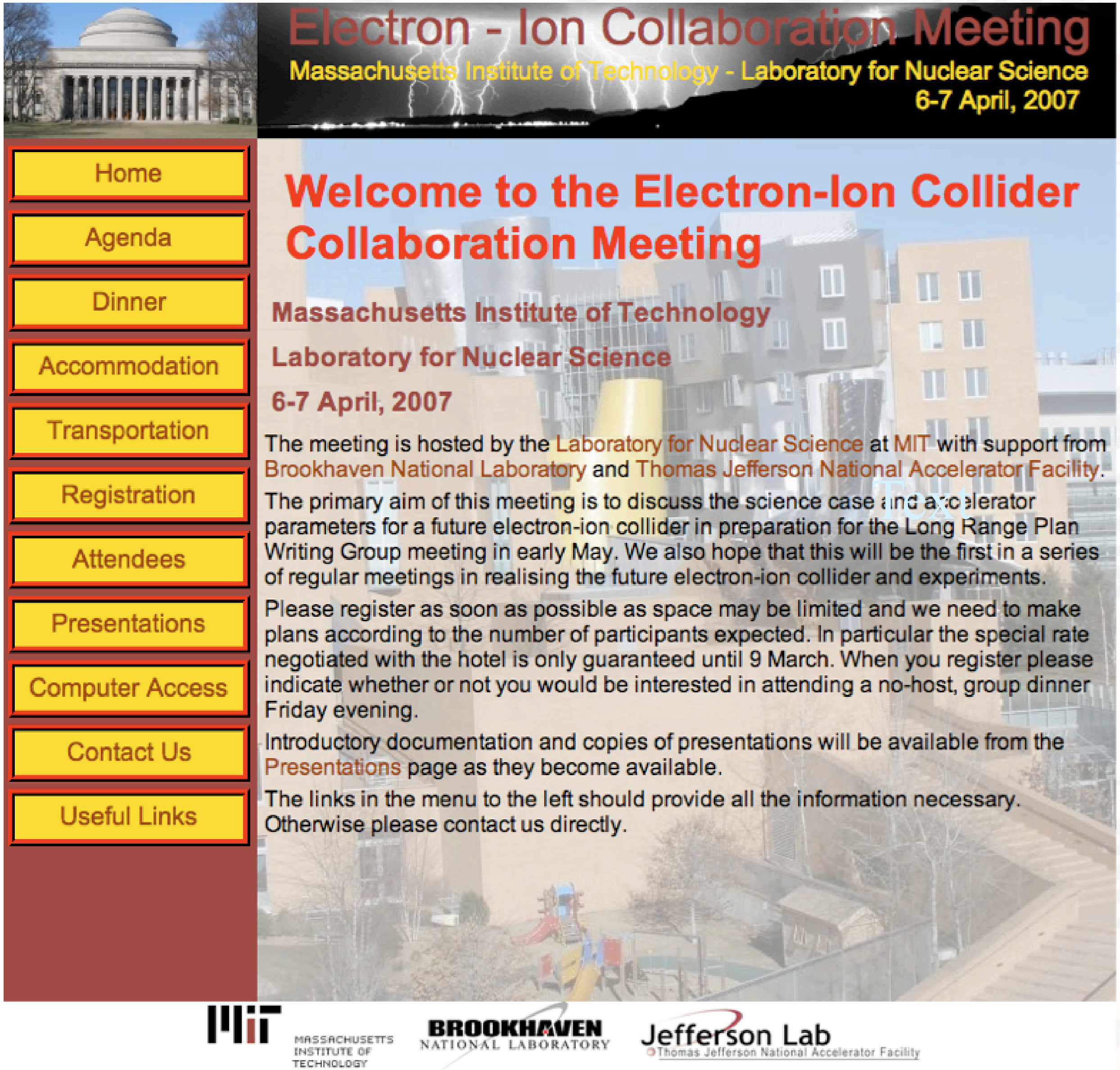
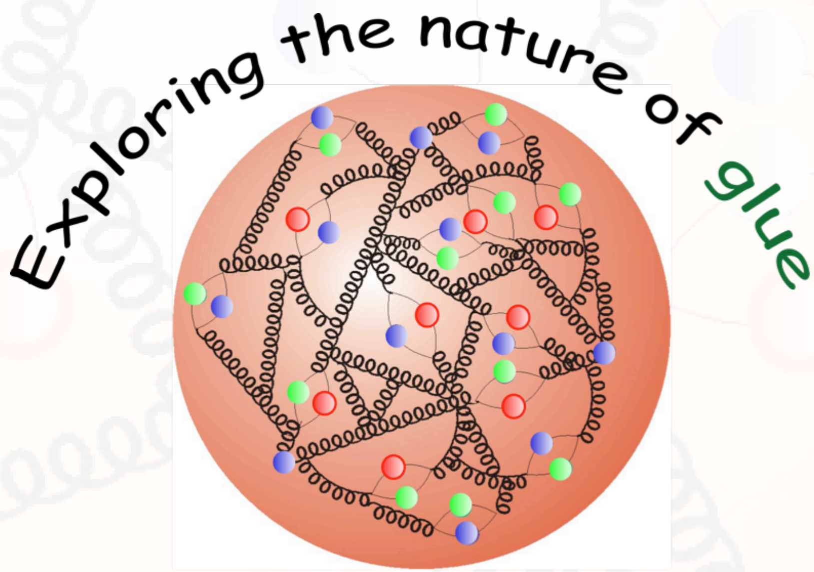
The Electron-Ion Collider



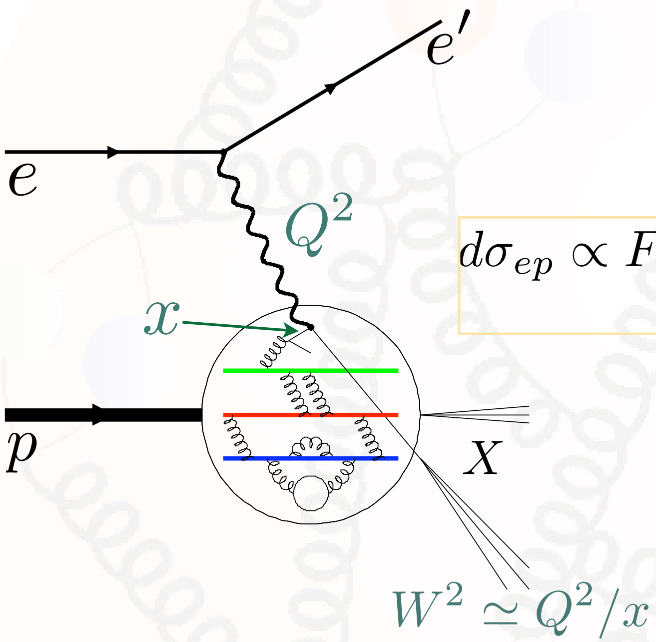
http://www2.lns.mit.edu/eic

Outline

- Future opportunities: Polarized ep physics
- Future opportunities: Low-x physics
- Concepts and Status
- Summary and Outlook

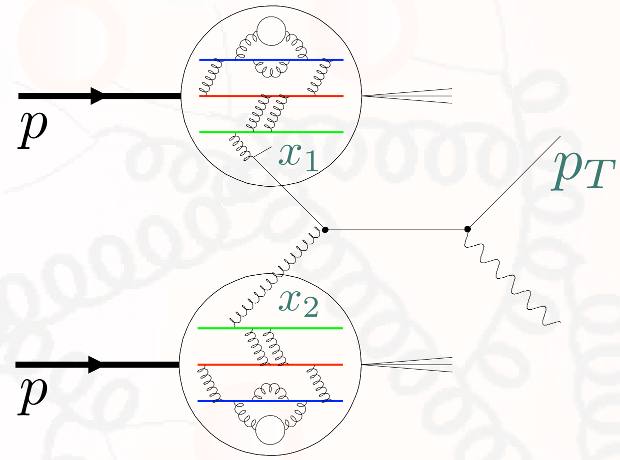


- How do we probe the structure and dynamics of matter in ep / pp scattering?



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

Universality

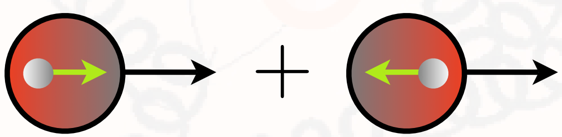


$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

Factorization

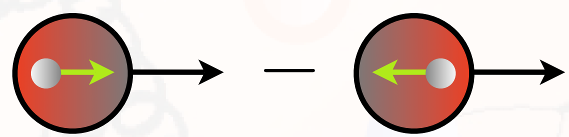
Momentum contribution

$$f(x) =$$



$$f^+(x) + f^-(x)$$

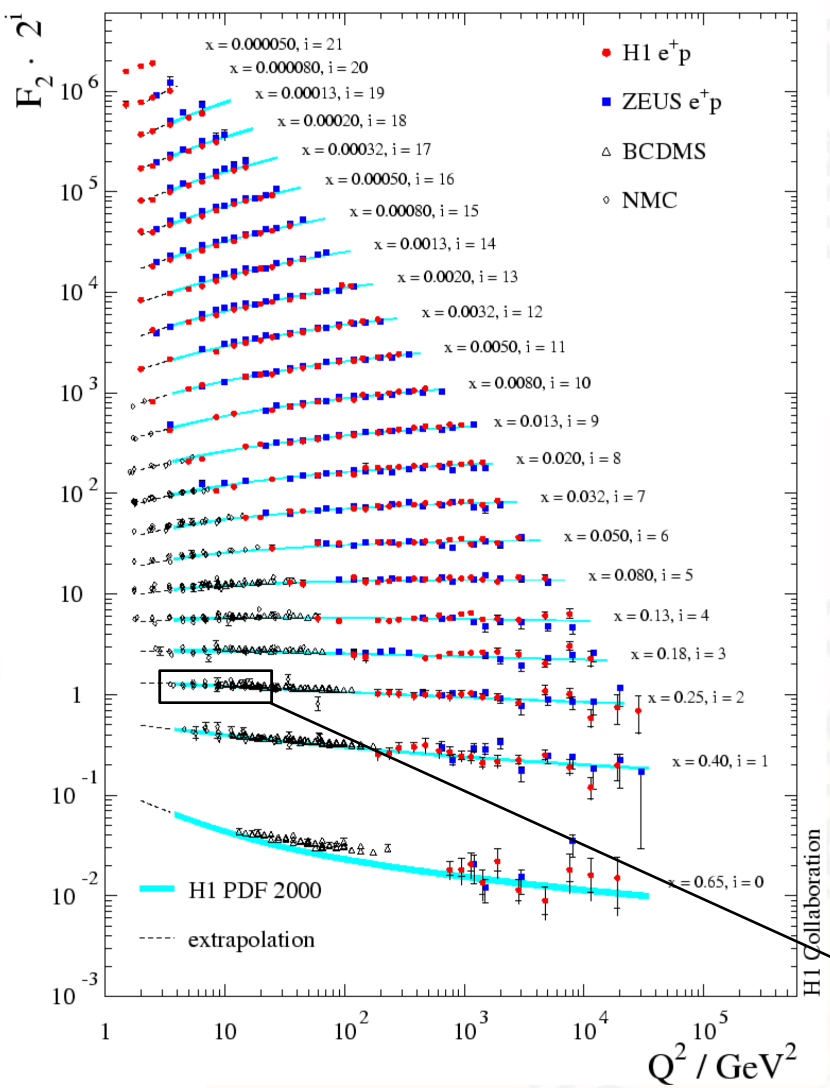
$$\Delta f(x) =$$



$$f^+(x) - f^-(x)$$

Spin contribution

What do we know about quarks/gluons? Momentum contribution to proton

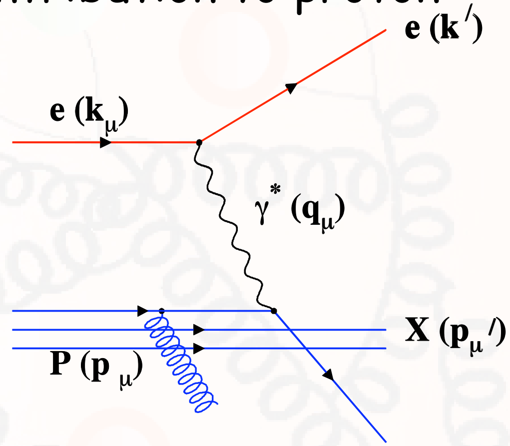


Strong violation of scaling at low x and high Q^2

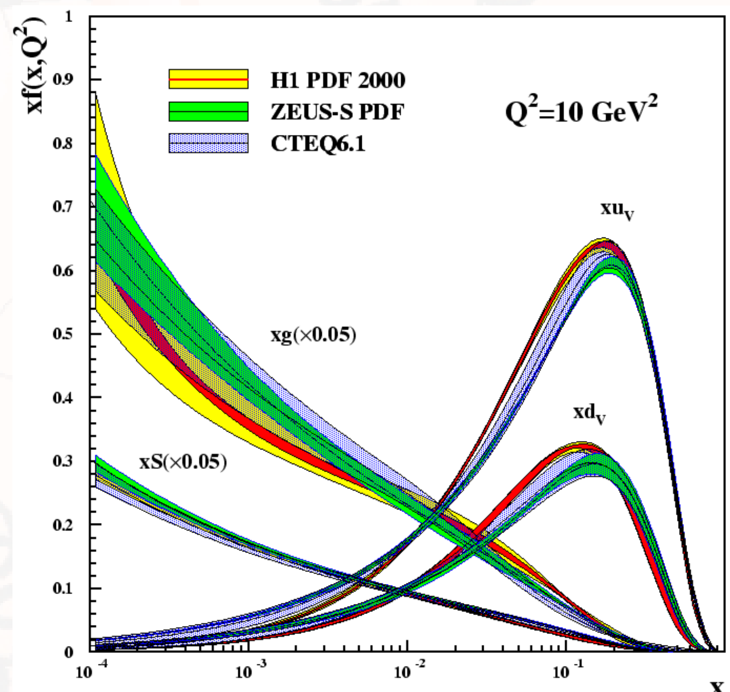
$$xg \propto \left(\frac{dF_2}{d\ln Q^2}\right)$$

In contrast to:

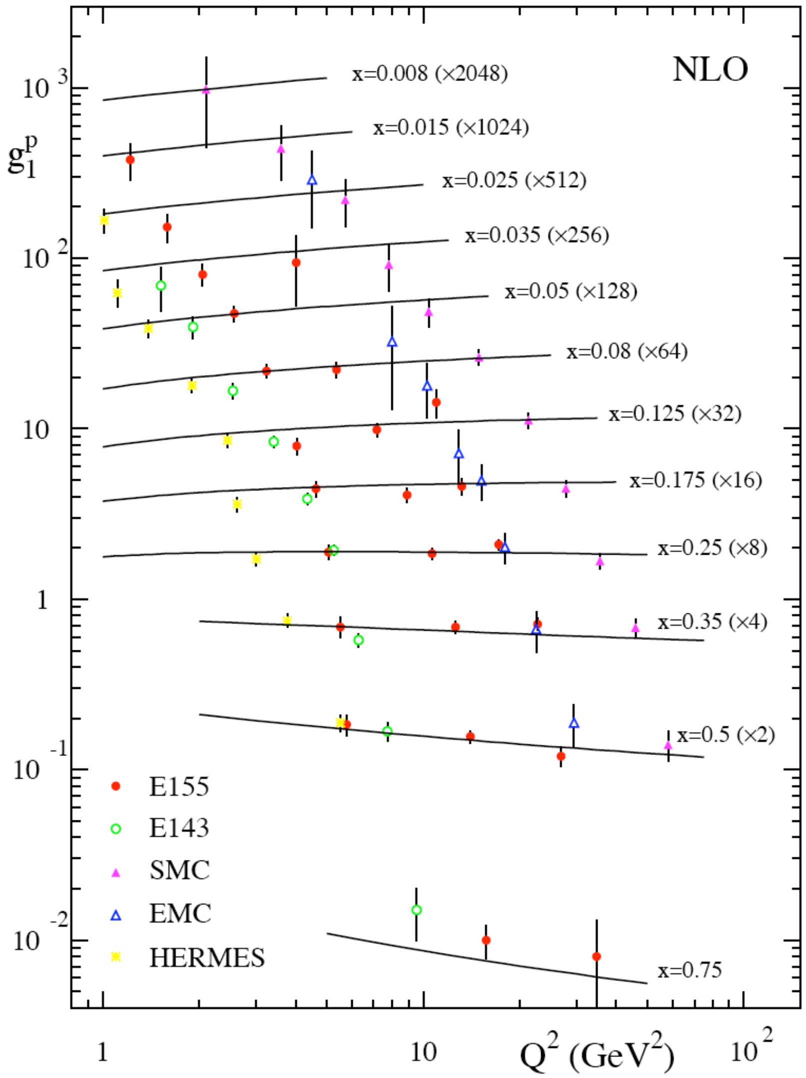
Low Q^2 high x!

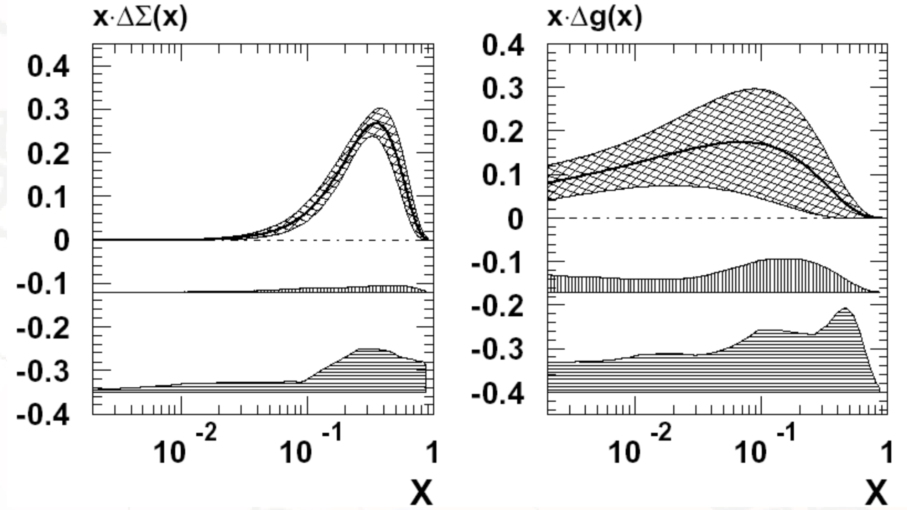


Evolution



What do we know about quarks/gluons? Spin contribution to proton





- EMC/SMC result: Fraction of proton spin carried by quarks is small:

$$\Delta\Sigma_{(\mathrm{AB})} = 0.38\,^{+\,0.03}_{+\,0.03} \quad \text{at} \quad Q^2 = 1\,\mathrm{GeV}^2$$

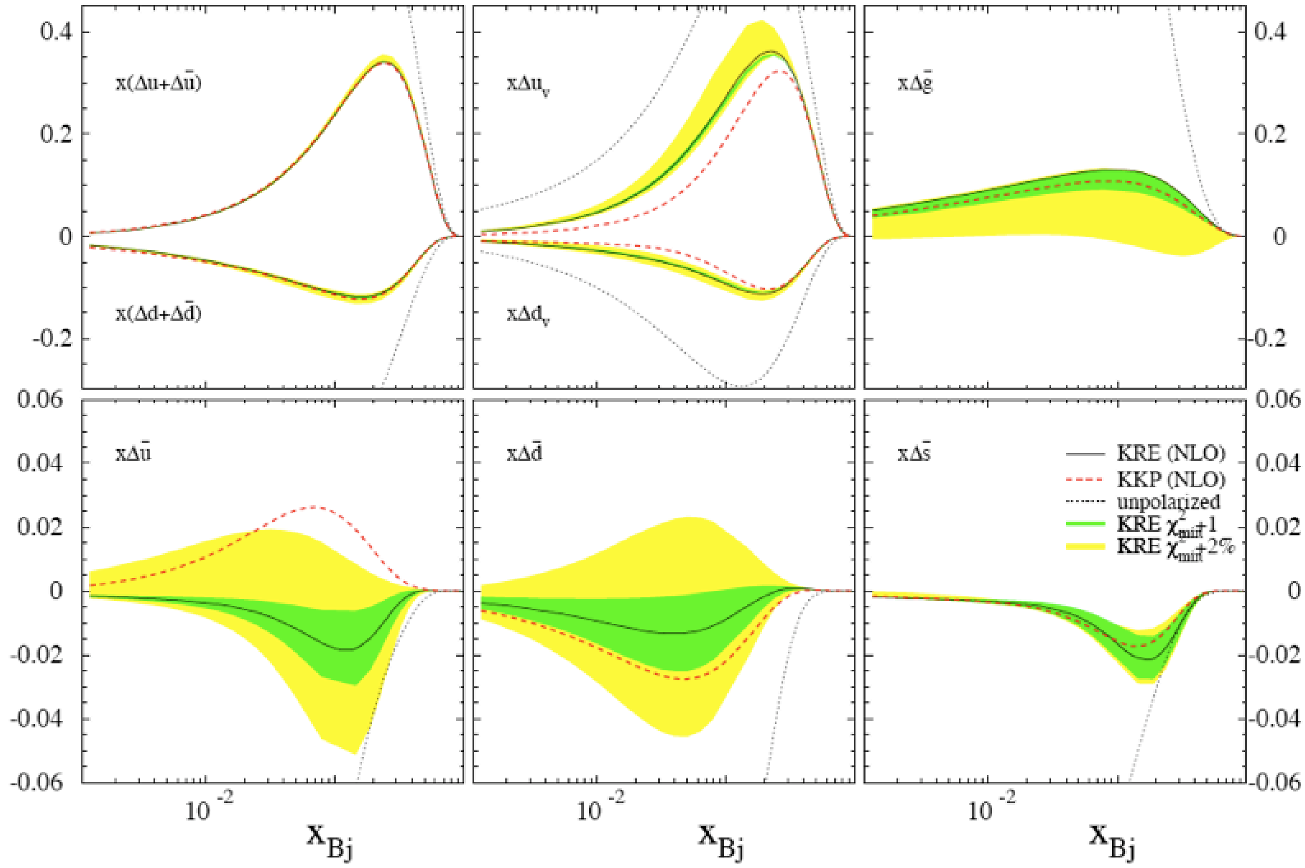
- At present: ΔG is only poorly constrained from scaling violations in fixed target DIS experiments

$$\Delta G_{(\mathrm{AB})} = 0.99\,^{+\,1.17}_{+\,0.31} \quad \text{at} \quad Q^2 = 1\,\mathrm{GeV}^2$$

B. Adeva et al., SMC Collaboration, Phys. Rev. D58 (1998) 112002.

What do we know about quarks/gluons? Spin contribution to proton

- Recent global analysis (FS) including inclusive and semi-inclusive polarized DIS data
- Anti-quark (u/d/s) distributions and gluon distributions unstrained
- Important future constrain from: RHIC-SPIN and EIC

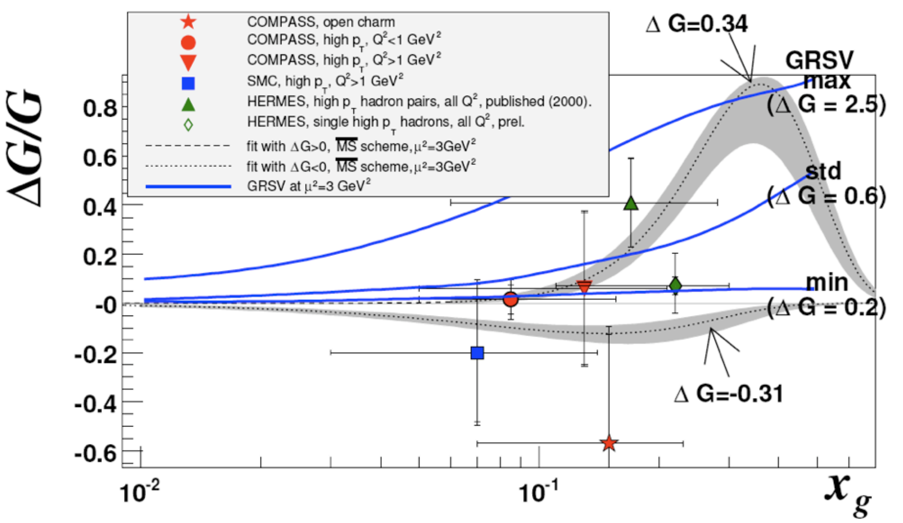


D. de Florian et al., Phys. Rev. D71, 094018 (2005).

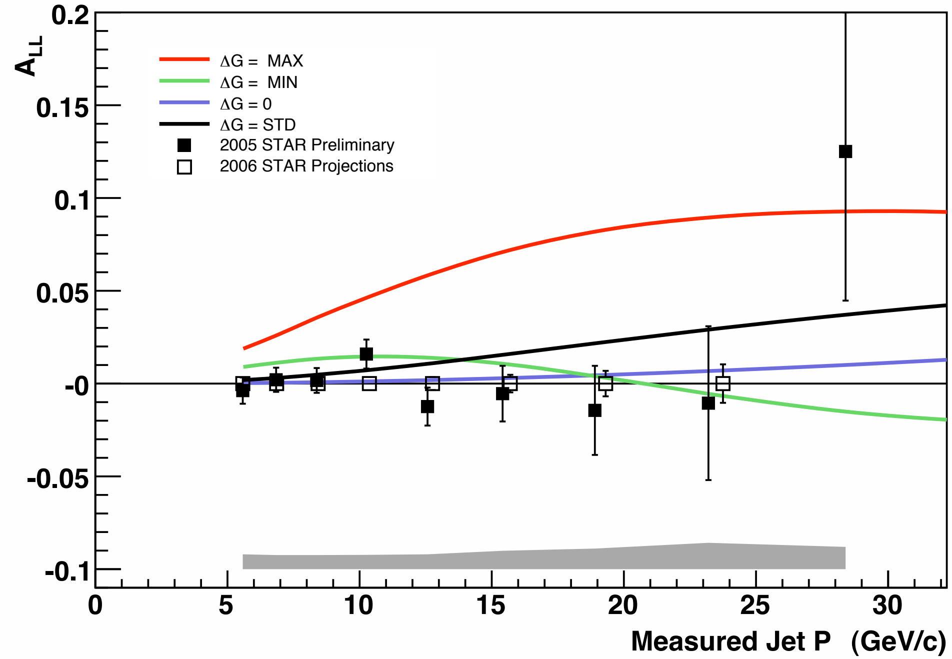
$$\boxed{\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2)dx}$$

$$\boxed{\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2)dx}$$

- Polarized fixed-target experiments and polarized pp experiments



$$x_{\rm parton} \simeq 2p_T/\sqrt{s}$$

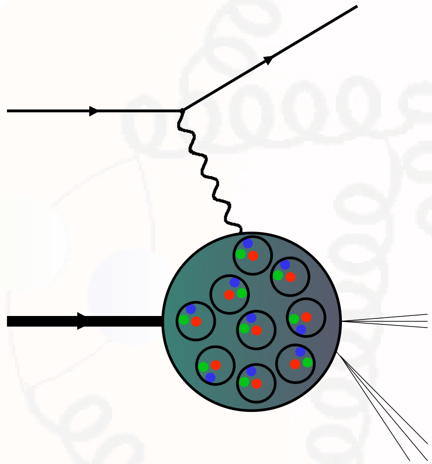


- High-p_T and open charm polarized DIS data: LO extraction of gluon polarization
- RHIC-SPIN: Recent data important constrain on gluon polarization (Global analysis needed!)

Large gluon polarization in measured kinematic region disfavored

- How do we probe the structure and dynamics of matter in eA / pA scattering?

$$Y_+ = 1 + (1-y)^2$$



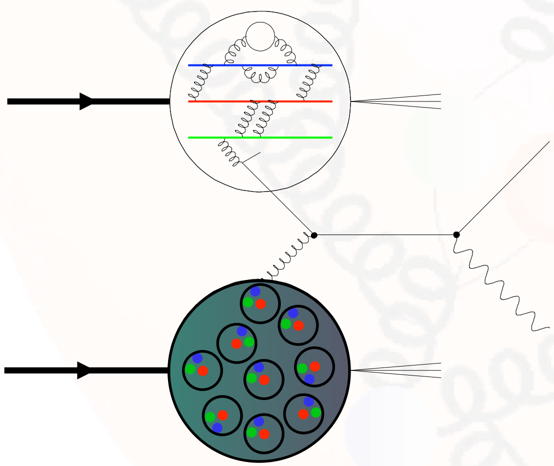
$$\boxed{\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)}$$

$$\sigma_{tot}^{\gamma^* p} = \sigma_T^{\gamma^* p} + \sigma_L^{\gamma^* p}$$

$$F_2 = \frac{Q^2}{4\pi^2\alpha}\sigma_{tot}^{\gamma^* p} = \sum_{f=q\bar{q}} x e_q^2 f$$

$$F_L = \frac{Q^2}{4\pi^2\alpha}\sigma_L^{\gamma^* p} \propto xg$$

Universality



$$\boxed{d\sigma = \sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to f X} \otimes D_f^h}$$

Factorization

Important: Complementary probes are required for unambiguous extraction of observables in high-energy density QCD region!

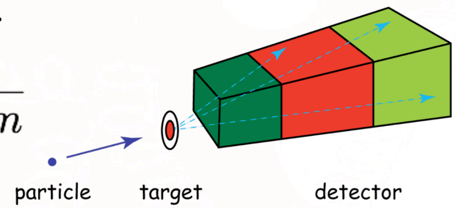
Low-x basics

Access higher parton density system

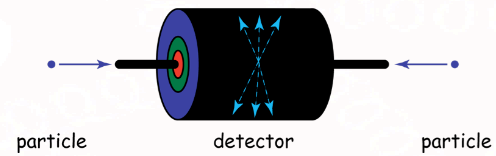
- Larger center-of-mass energy (√s): Smaller x at larger √s!

fixed-target

$$\sqrt{s} = \sqrt{2E_B m}$$



$$x \sim \frac{Q^2}{s}$$



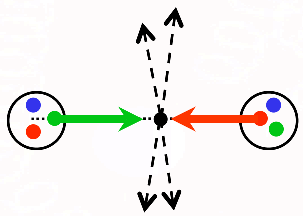
collider

$$\sqrt{s} = \sqrt{4E_{b_1}E_{b_2}}$$

- Forward direction: Smaller x at larger at larger η!

central

(η ≈ 0)

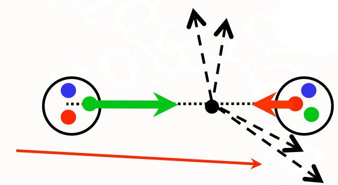


$$x \sim \frac{2p_T}{\sqrt{s}} e^{-\eta}$$

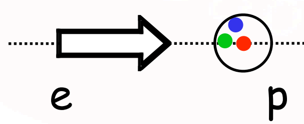
forward

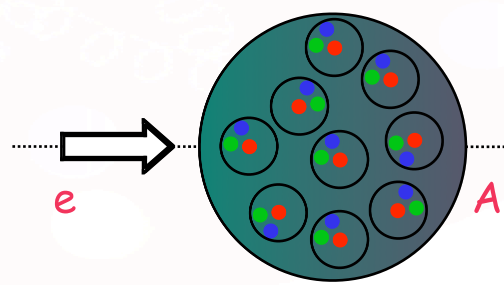
(η large)

(η ≈ 0)



- eA vs. ep scattering: Probe higher parton density system in eA compared to ep!

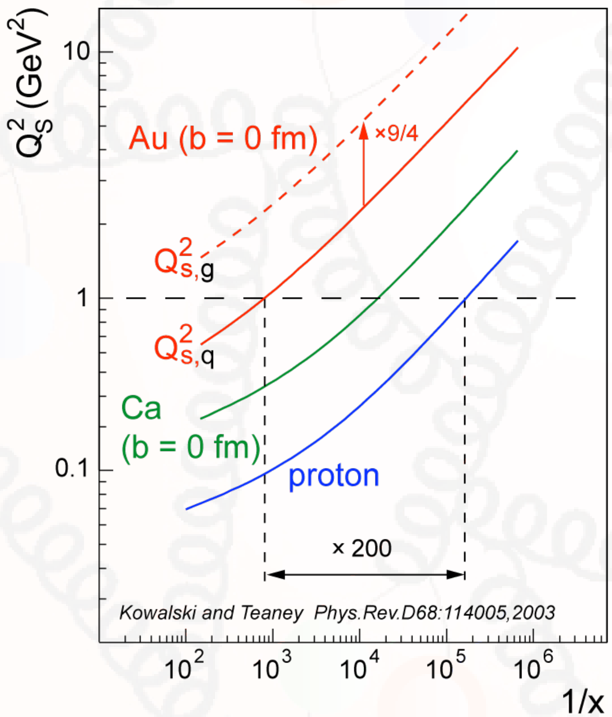


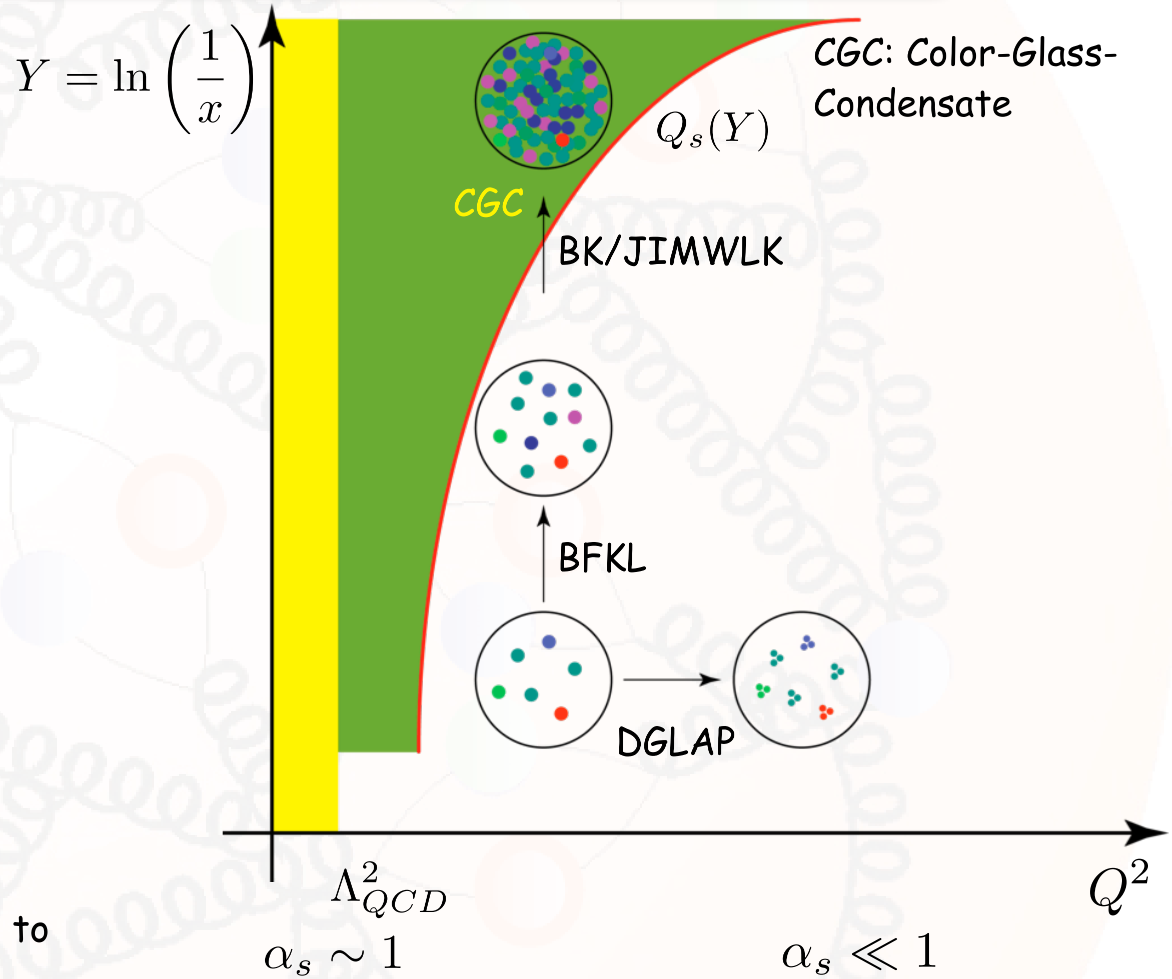


$$\sim A^{1/3}$$

Bernd Surrow

- Low-x basics
  - Dynamics: DGLAP / BFKL and CGC





Q_s^2: Saturation scale ⇒ Characterize transition to saturation region!

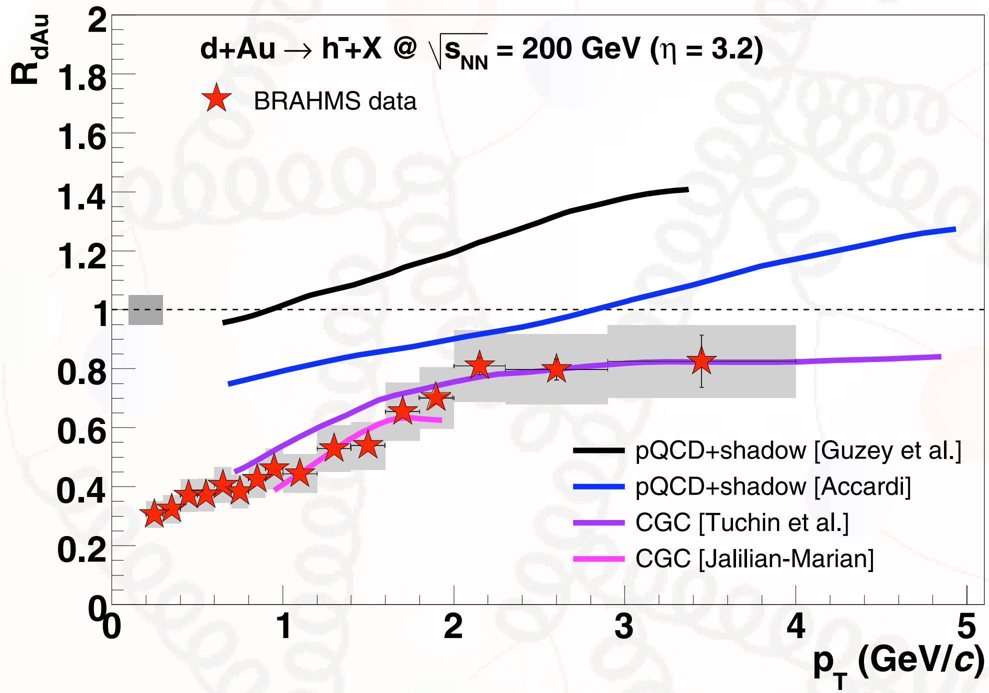
$$Q_s^2 \simeq \alpha_s \frac{1}{\pi R^2} xG(x, Q^2) \sim A^{1/3} x^{-\delta}$$

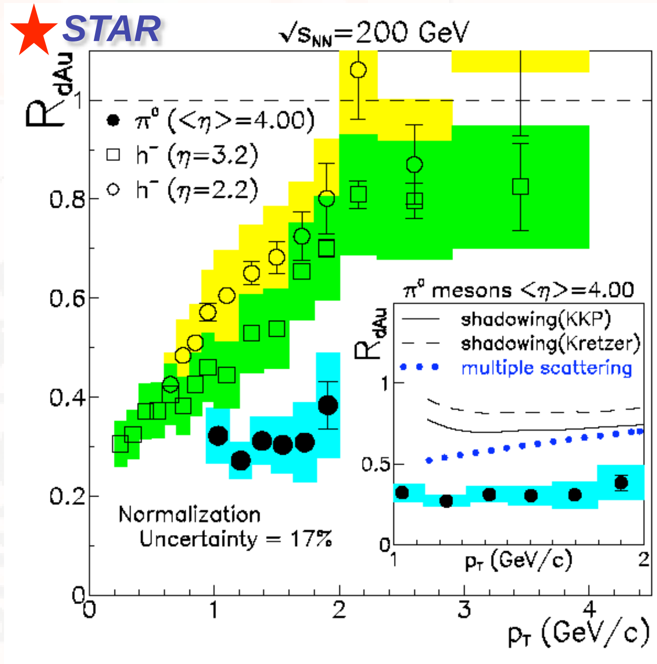
Enhanced for eA compared to ep:

DGLAP: Evolution in Q^2

BFKL: Evolution in x

RHIC dA scattering at forward η

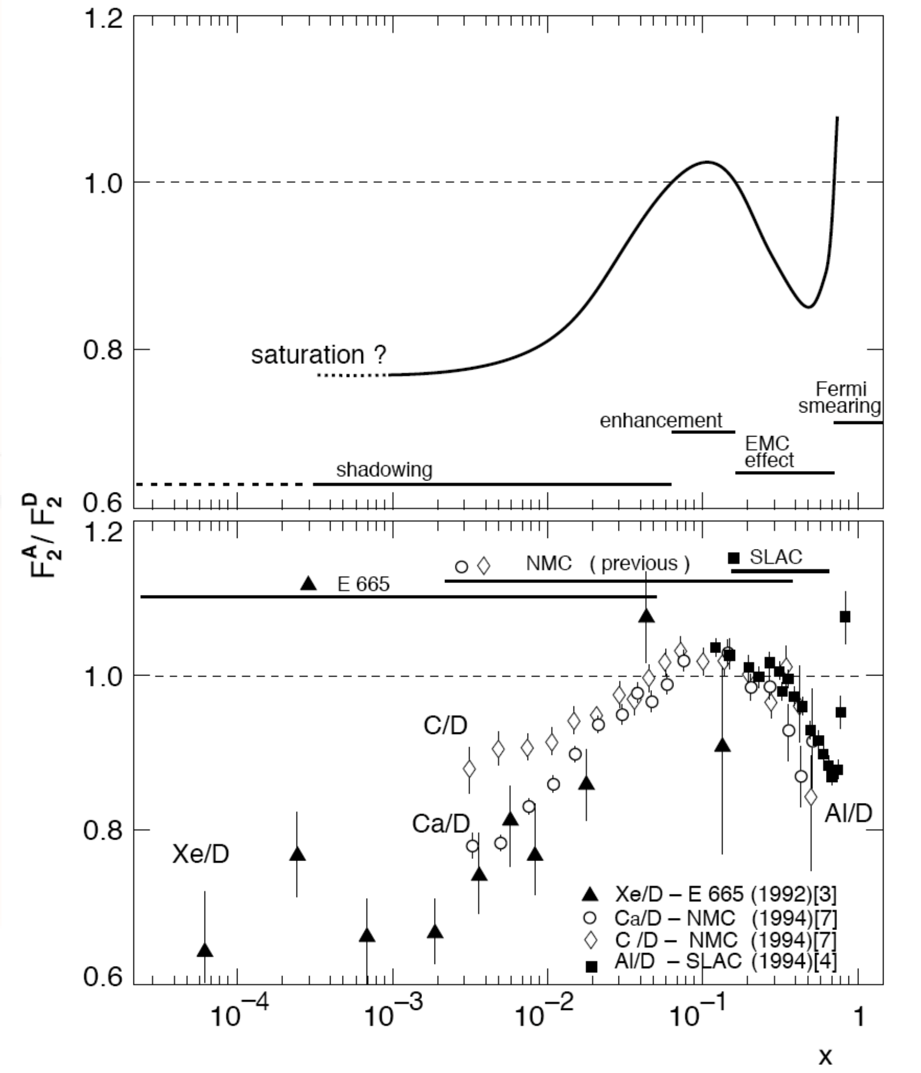


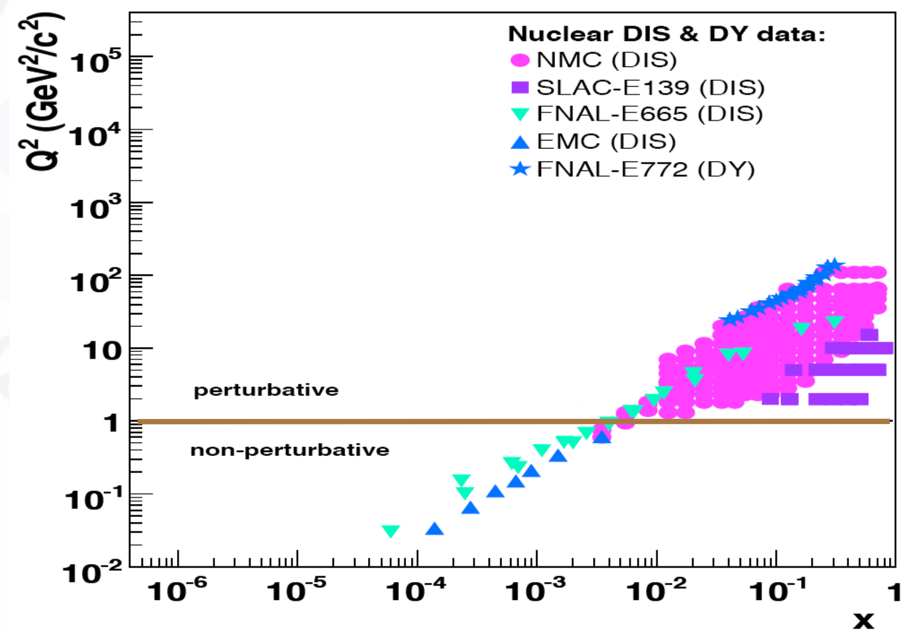


- Forward identified hadron production at RHIC in dAu collisions: Sizable suppression of yields for charged hadrons and neutral pions observed
- pQCD+shadowing calculations over-predict hadron yield suppression. Is this an indication for gluon saturation in Au nuclei?
- More RHIC dAu are expected with enhanced detector capabilities (PHENIX/STAR)

Concepts and Status: Low-x Physics

- Fixed-target scattering

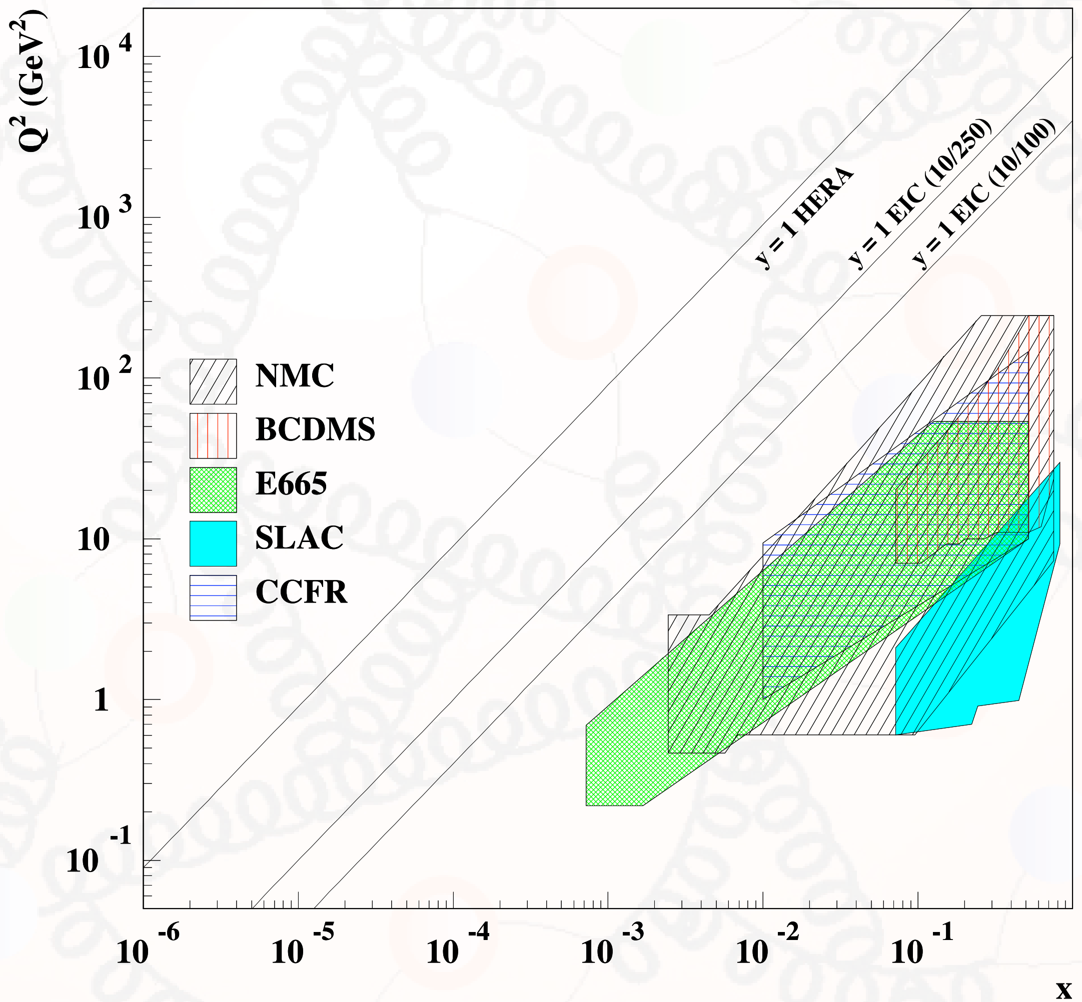




- Inclusive structure function ratio important to constrain nuclear modifications to gluon density
- World data (Fixed target) are concentrated above $x>0.01$ in pQCD region
- For $x<0.01$ only data in non-pQCD region

Future Opportunities

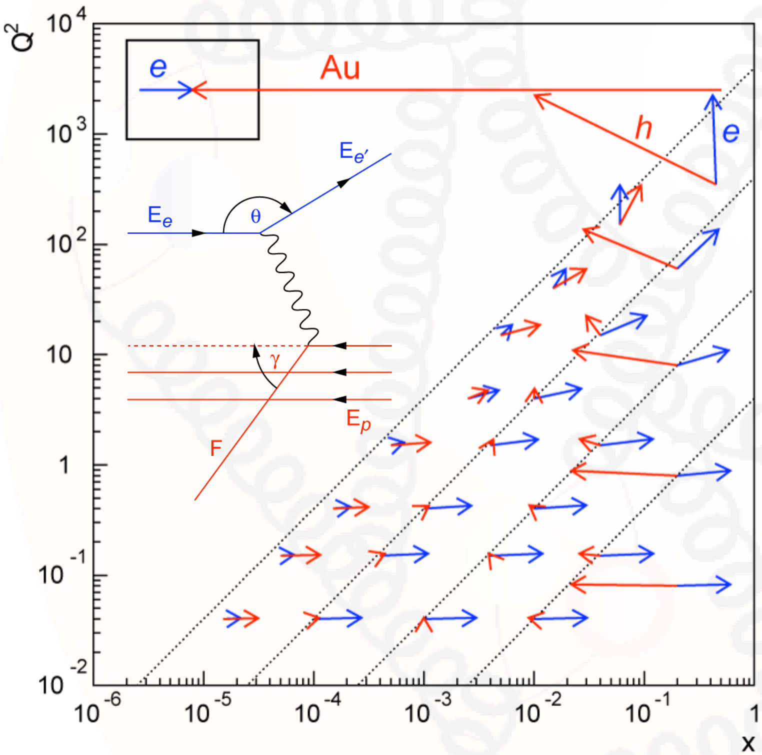
- Kinematics
  - Comparison HERA / EIC / Fixed-target experiments

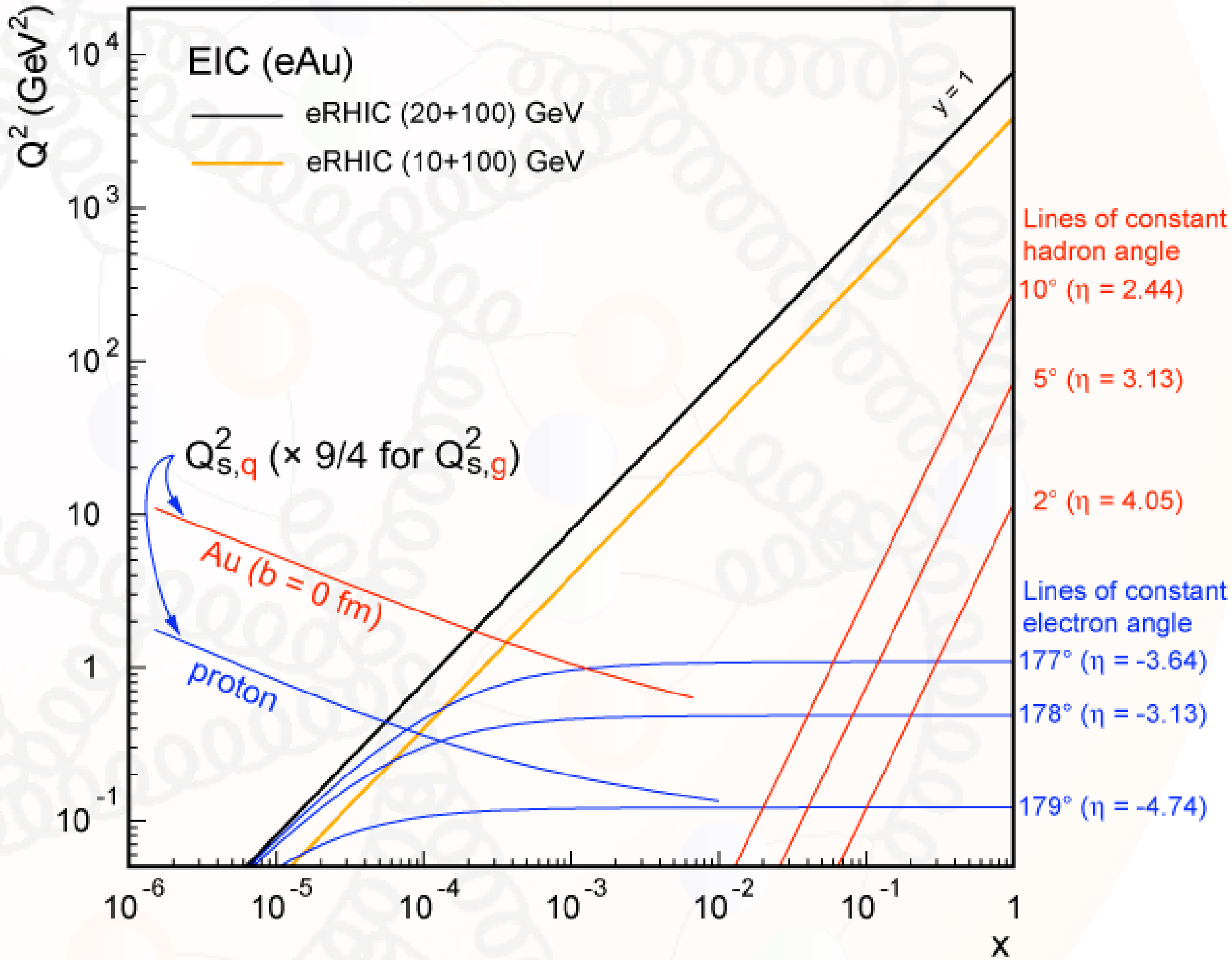


Kinematics

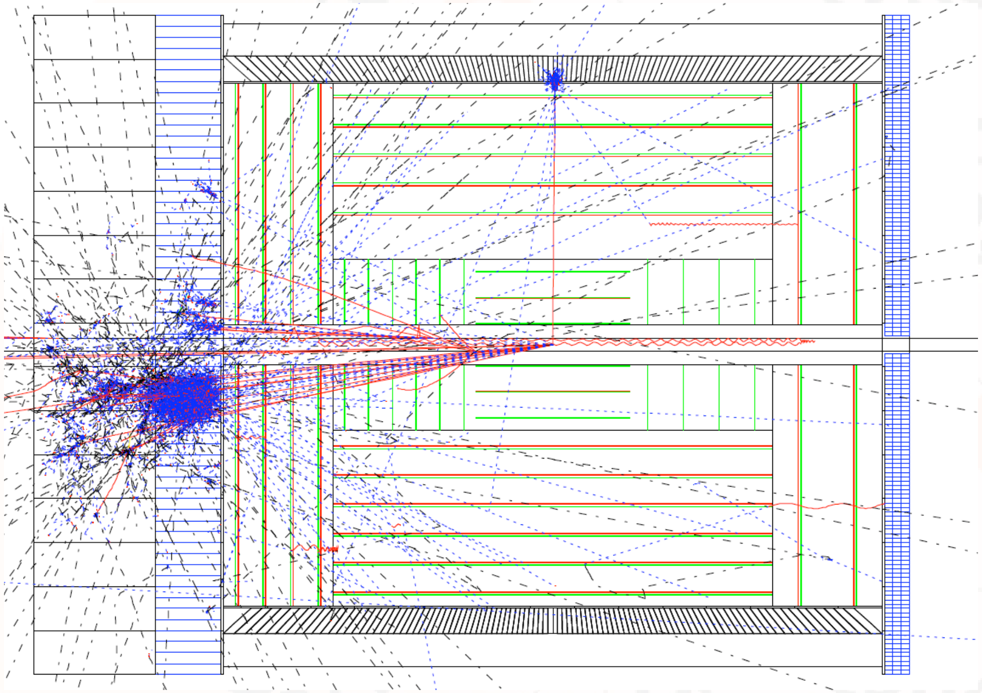
Acceptance

EIC (eA) event topology (E_e=10 GeV, $E_{n/A}$=100 GeV)

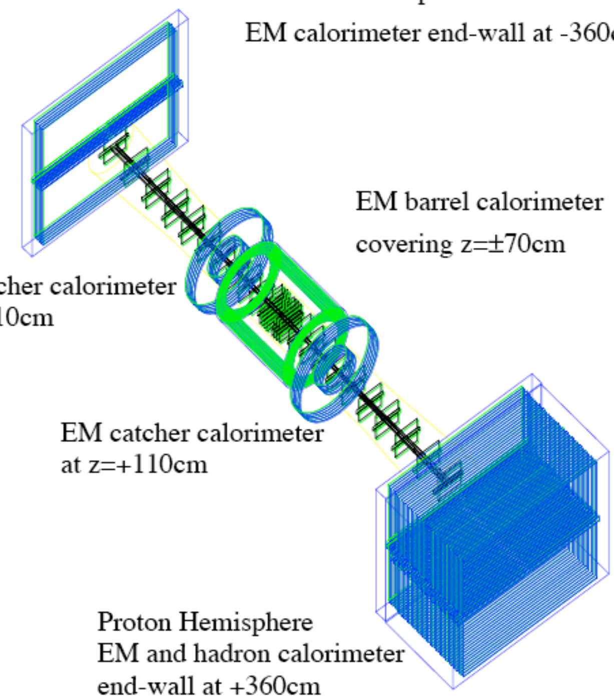




Facilities - Detector concepts



J. Pasukonis, B. Surrow, physics/0608290



I. Abt, A. Caldwell, X. Liu, J. Sutiak, hep-ex 0407053

Concepts:

- Focus on the rear/forward acceptance and thus on low-x / high-x physics (Compact system of tracking and central electromagnetic calorimetry inside a magnetic dipole field and calorimetric end-walls outside
- Focus on a wide acceptance detector system (Compact calorimeter system)

- Unpolarized ep/eA physics
  - Precision measurement of F_2 at low x: Transition from hadronic to partonic behavior
  - Precision measurement of the longitudinal structure function F_L
  - Precision measurement of F_2 at high x
  - Measurement of diffractive and exclusive reactions
  - DVCS
  - Precision measurement of eA scattering

Inclusive measurement involving electron at small polar angles (≈10mrad)

Inclusive measurement involving electron (Low x) - Variable √s

Inclusive measurement (hadronic final state in forward direction): Good forward acceptance

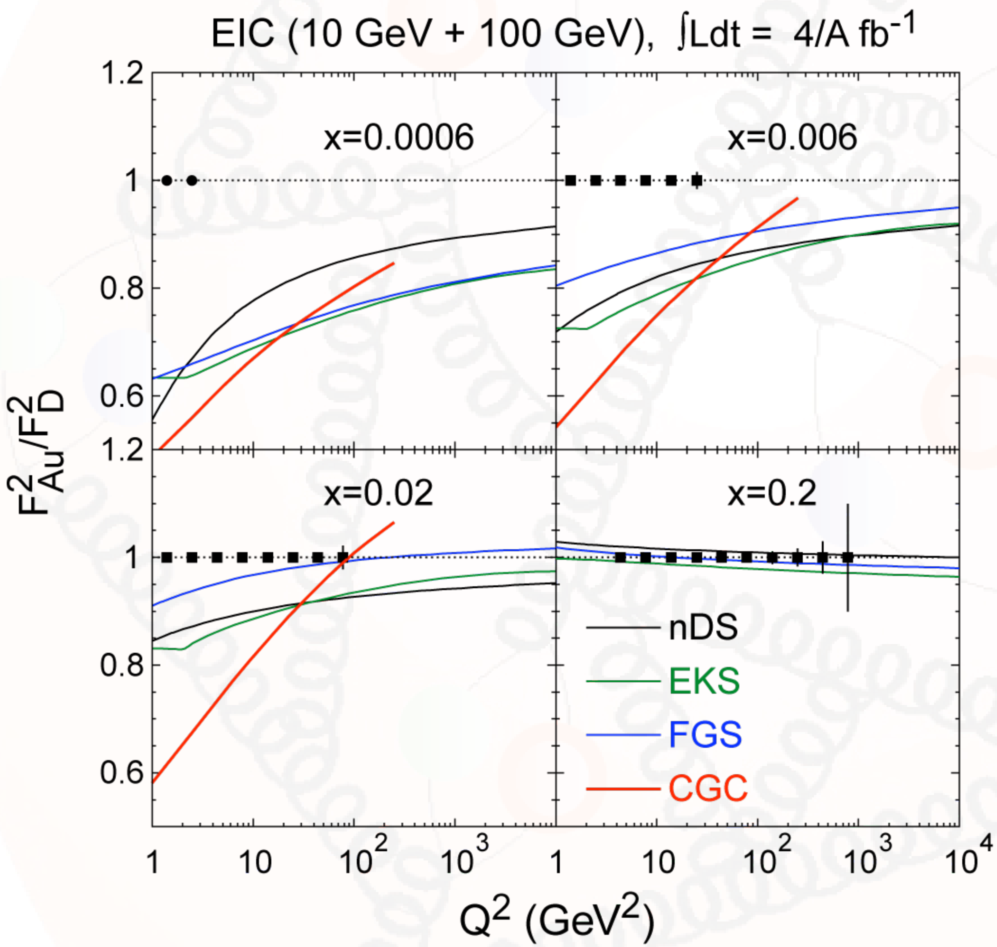
Forward p tagging system

Forward p tagging system - photon/electron discrimination Variable √s and positrons

Similar to ep case at low x - High x: Forward acceptance - careful study necessary!

Future Opportunities: Low-x physics

- Observables: Nuclear structure function ratios



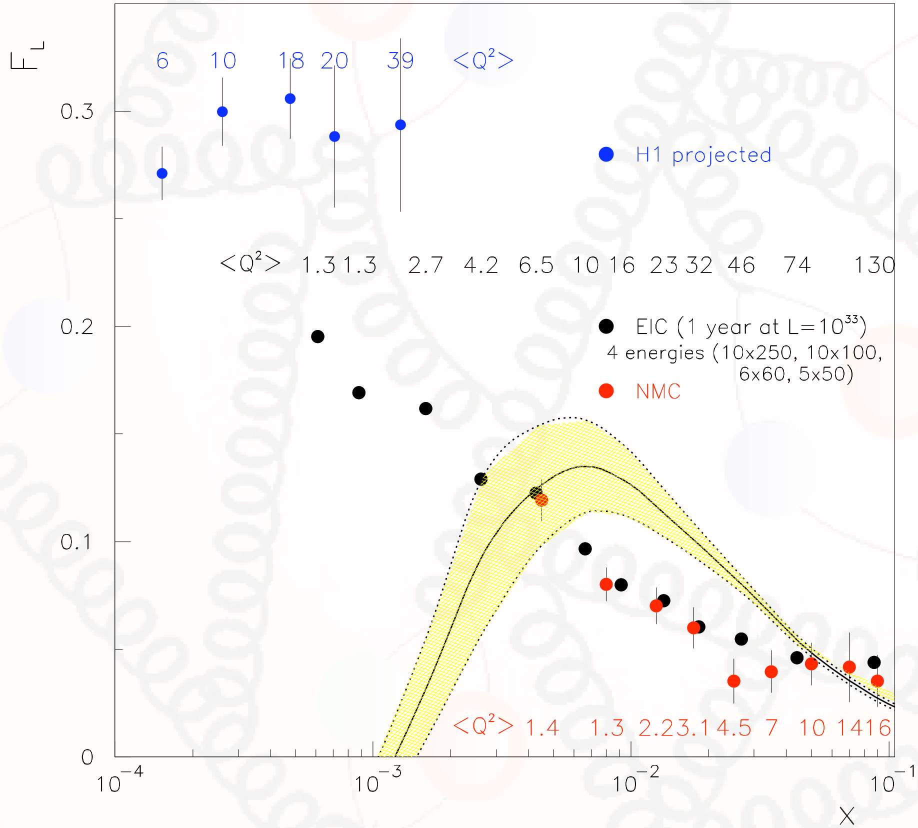
$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

- F_2 will be one of the first measurements at EIC
- nDS, EKS, FGS: pQCD models with different amounts of shadowing

EIC will allow to distinguish between pQCD and saturation model predictions

Future Opportunities: Low-x physics

- Observables: Longitudinal structure function



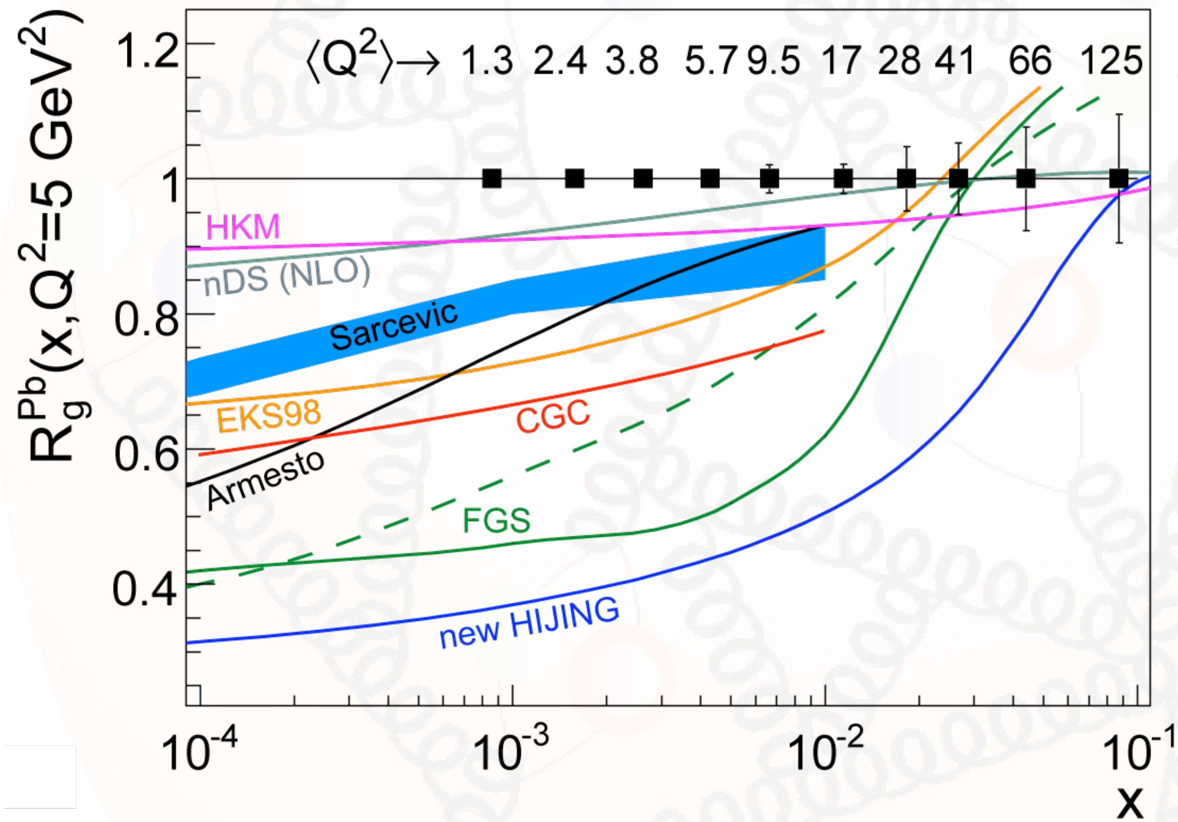
$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right) \qquad F_L = \frac{Q^2}{4\pi^2\alpha}\sigma_L^{\gamma^* p} \propto xg$$

- F_L measurement requires operation of EIC at different center-of-mass energies ($\sqrt{s}$)
- Precise measurement from low to high Q^2 region

Unique measurement at EIC of F_L with high precision in ep collisions to constrain gluon distribution

Future Opportunities: Low-x physics

- Observables: Ratio of nuclear gluon distribution function



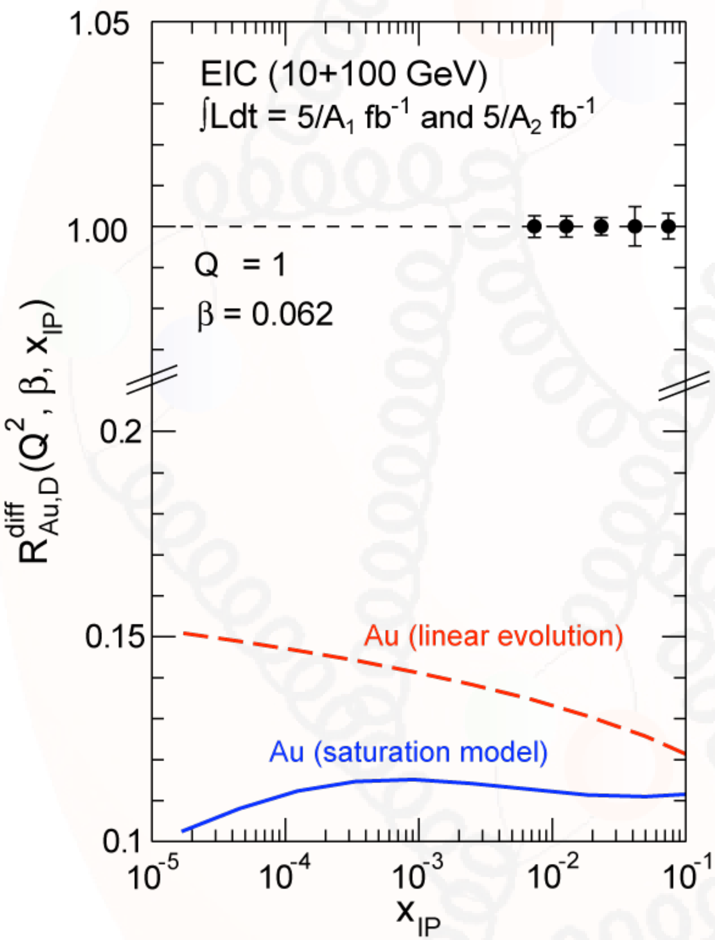
- EIC will reach the unmeasured low-x region (<0.01) with high precision for Q^2>1GeV^2
- Constrain gluon modification due to nuclear effects in comparison to large range of models

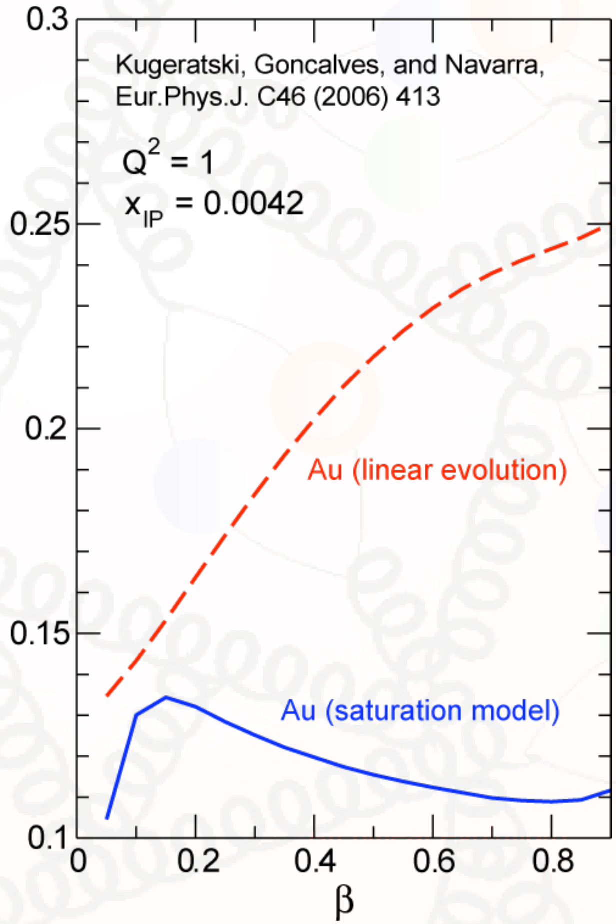
EIC will measure modification of gluon distribution with high precision!

$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right) \quad F_L = \frac{Q^2}{4\pi^2\alpha}\sigma_L^{\gamma^* p} \propto xg$$

Future Opportunities: Low-x physics

- Observables: Diffractive measurements





x_{IP} = momentum fraction of the Pomeron with respect to the hadron

β = momentum fraction of the struck parton with respect to the Pomeron

$x_{IP} = x/\beta$

EIC allows to distinguish between linear evolution and saturation models in diffractive scattering with high precision

Polarized ep physics- Future Opportunities

- Polarized ep physics
  - Precision measurement of g^p_1 over wide range in Q^2
    - Extraction of gluon polarization through DGLAP NLO analysis
    - Extraction of strong coupling constant
  - Precision measurement of g^n_1 (neutron) (Polarized ^{3}He)
  - Photoproduction measurements
  - Electroweak structure function g_5 measurements
  - Flavor separation through semi-inclusive DIS
  - Target and current fragmentation studies
  - Transversity measurements

Inclusive measurement - electron (Low x) and hadronic final state (High x) over wide acceptance range

In addition: p tagging in forward direction

Jet production and small-angle e tagger

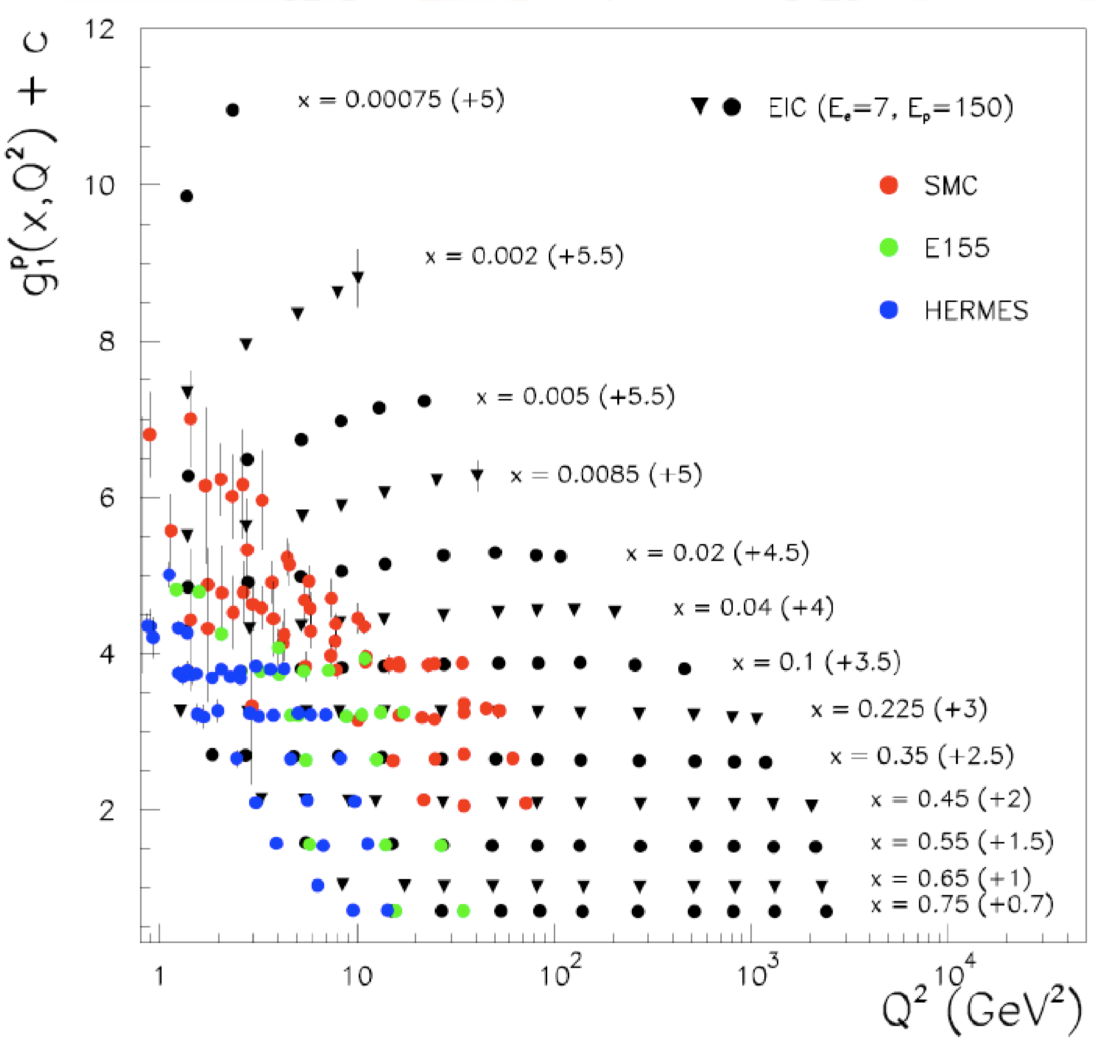
Hermetic detector configuration / e^- and e^+ Missing energy measurement

K/π separation - particle ID - Heavy flavor - Secondary vertex reconstruction and J/Psi (Forward muons)

Forward acceptance: Tracking and calorimetry

Polarized ep physics- Future Opportunities

- Observables: g^1_p as a function of Q^2

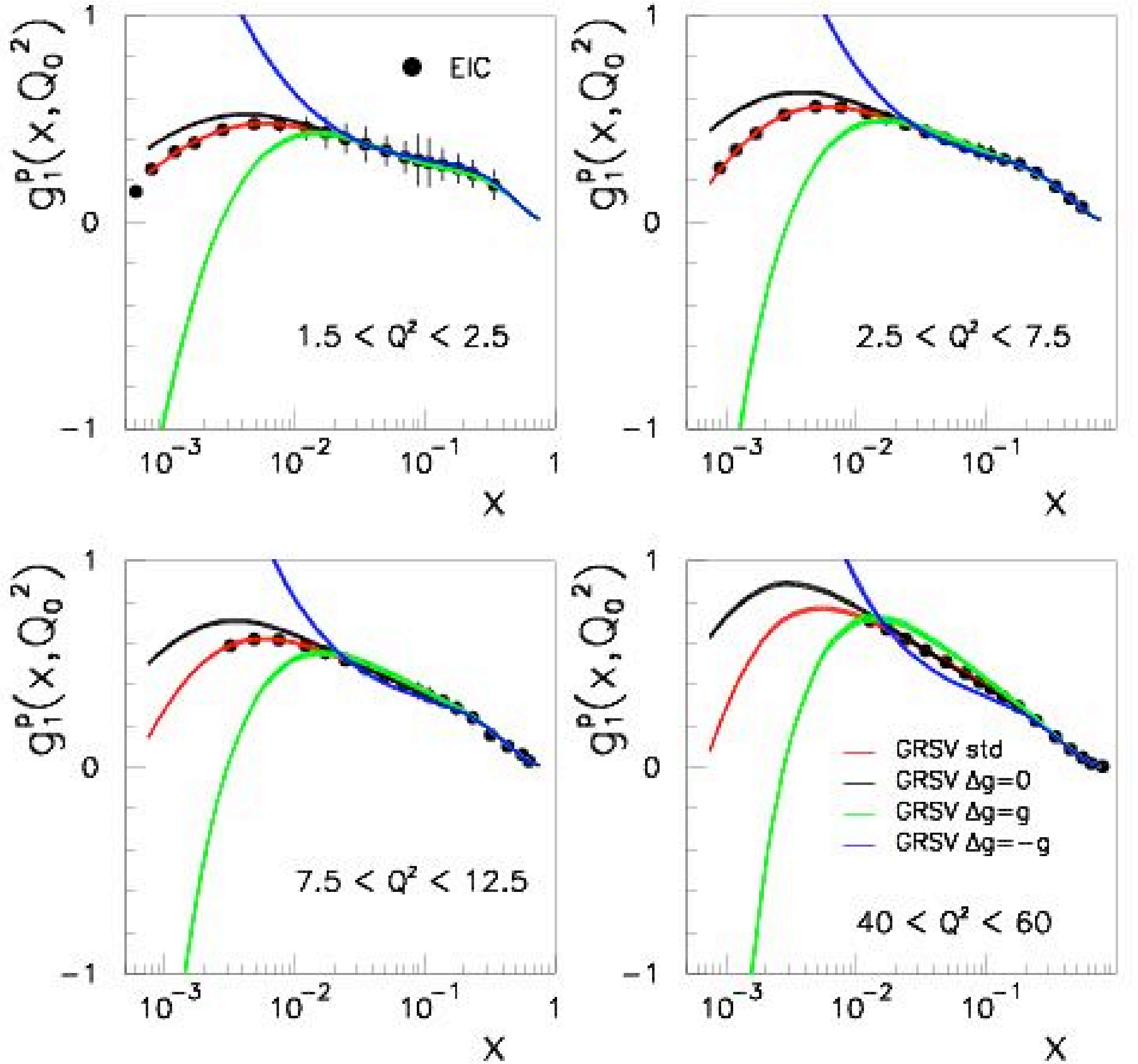


- E_e = 7GeV and E_p = 150GeV
- Luminosity: 5fb^{-1}

EIC allows a precision measurement of g^1_p over wide range in Q^2 compared to previous experiments

Polarized ep physics- Future Opportunities

- Observables: g^1_p as a function of x

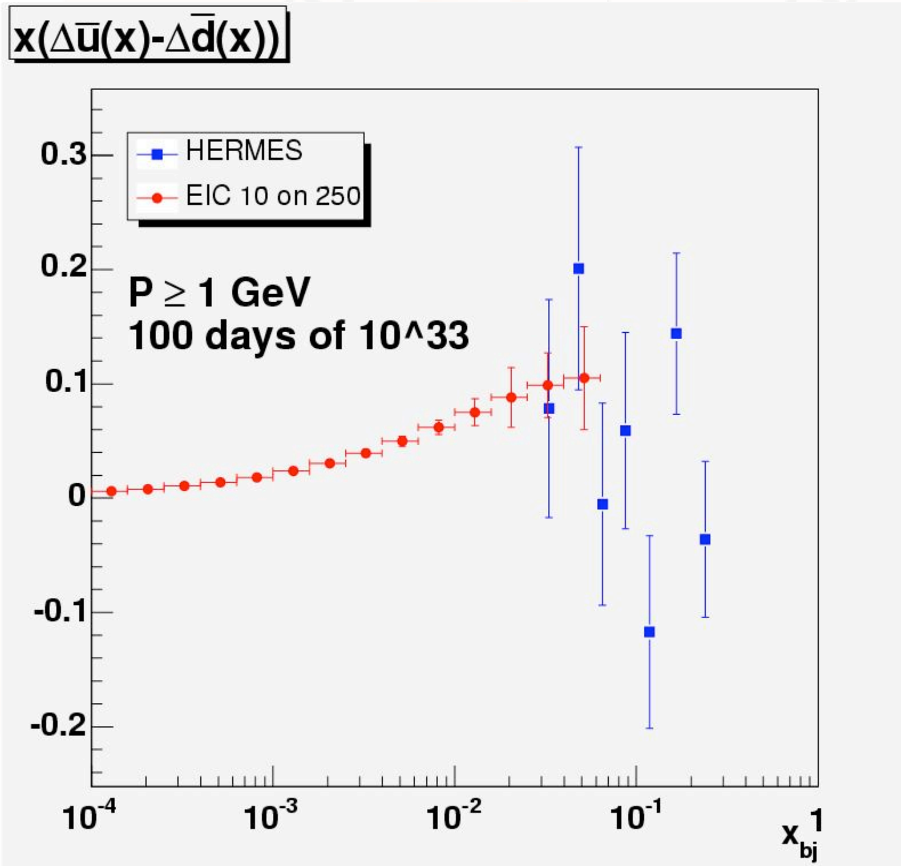


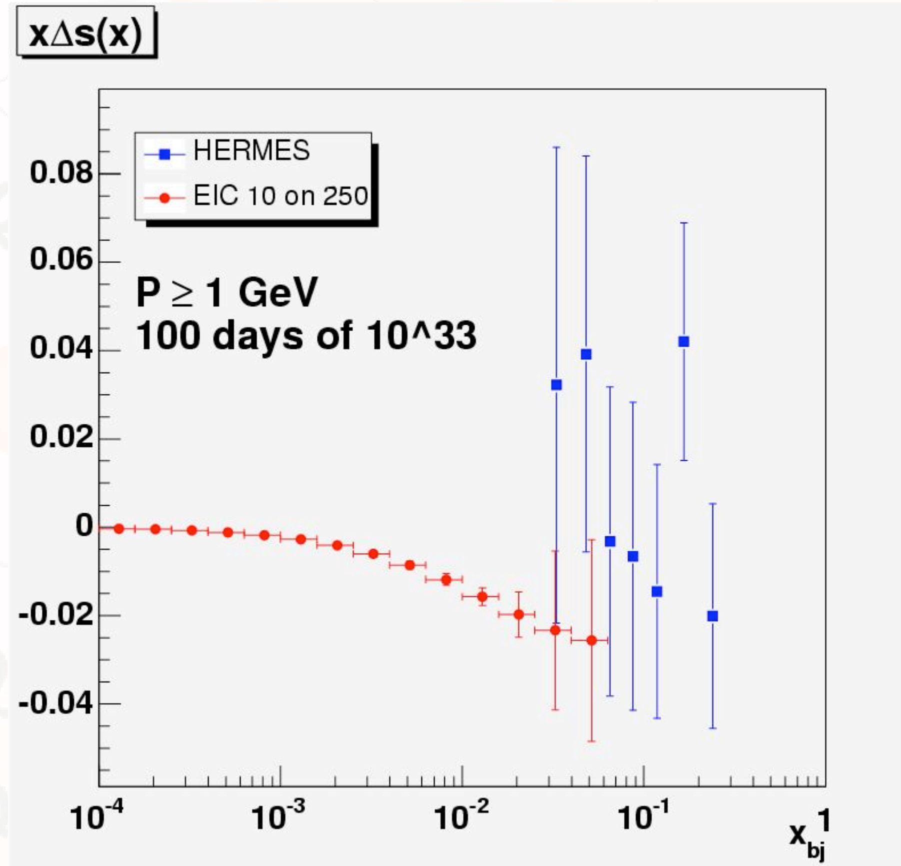
- E_e = 7GeV and E_p = 150GeV
- Luminosity: $5fb^{-1}$

EIC allows a precision measurement of g^1_p at lower x values compared to previous experiments

Polarized ep physics- Future Opportunities

- Observables: Quark flavor distributions





- Semi-inclusive DIS (Tagging of identified hadrons)
- Also: W/Z exchange

Summary and Outlook

- Status and Concepts

  - HERA: Precision structure function measurements (F_2) at low x
  - At low Q^2 and low x: DGLAP (Leading twist) approach leads to valence-like gluon behavior
  - Diffraction: Important contribution to overall ep event yield
  - Dipole model: Allows to describe inclusive and diffractive measurements. Reach of saturation region at low x not conclusive
  - Lesson: Optimize any future EIC efforts for acceptance and luminosity
  - eA: No information in low-x region
  - dAu results at RHIC: Can saturation account for observed behavior? Complementary probes important (RHIC/LHC)!
  - Important constrain on gluon polarization at high-x from semi-inclusive polarized DIS and RHIC-SPIN program - Complementary to EIC

Summary and Outlook

- Future Opportunities
  - EIC: First polarized ep collider - Precision measurement of polarized gluon distribution at low-x and quark flavor structure
  - EIC will allow to study the physics of strong color fields
  - Required: EIC at high luminosity and optimized detector
  - EIC will allow to bridge several QCD communities (Hadron structure and Relativistic Heavy-Ion)
  - Unique opportunity in precision QCD physics (The QCD LAB) complementary to other next generation facilities in Europe (LHC at CERN, FAIR at GSI) and Asia (J-PARC)